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A TEST CIRCUIT FOR CAPACITOR BANK GROUNDING STICKS

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JUNE 1992

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After completion of a charge-discharge cycle, energy-storage capacitor banks must be shorted to ground and the short maintained before the bank can be safely approached by an operator. It is essential that the grounding stick used by the operator to drain any residual charge have a proper electrical resistance. A test unit has been constructed and tested which checks the grounding circuit for proper resistance and provides a visual indication of its status. This unit also includes an auxiliary circuit which sounds an audible warning when an excessive current passes through the grounding circuit. The enhanced measure of safety which such a circuit could provide is illustrated by discussion of a recent capacitor-bank accident at Aberdeen Proving Ground, MD.

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1. INTRODUCTION

Since a typical capacitor in a modern capacitor bank can store 50 kJ of energy at a few tens of kilovolts, there are significant lethal hazards associated with the operation and maintenance of these energy storage devices. Perhaps the most insidious hazard is the charge buildup which can occur in unshorted capacitors when they are not in operation. This phenomenon, known as dielectric relaxation, involves the release of a charge which was previously trapped by absorption in the dielectric. Rand, Leep, and Bradley* measured the open terminal voltages of 10-kV capacitors with paper-castor oil dielectric following a particular operation cycle. They measured a peak voltage equal to 6% of the charge voltage approximately 13 hours after the cycle as a result of charge release in the dielectric. Because such voltages can be lethal,** it is essential that the capacitor's terminals be shorted immediately after operation and that this short be maintained until the capacitor is once again placed in service.

Following the operation of a capacitor bank, an operator should conduct a "safeing" operation by touching the center terminal of the capacitor with a grounding stick. The grounding stick is usually a metal contact attached to the end of an insulating rod. The metal contact is connected to a conducting cable which leads to a resistor permanently connected to the common ground of all the capacitors in the bank. When the operator touches the metal contact to the terminal of a capacitor, the resistor completes a discharge path between the terminals of the capacitor. He may then safely attach a wire to each terminal of the capacitor to continually drain any trapped charge which may be released. This procedure is repeated for each capacitor in the bank. Regardless of the prior conditions or events, the operator should always conduct a "safeing" operation immediately prior to touching a capacitor for maintenance.

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* Rand, J. L., R. W. Leep, and W. A. Bradley. "Design of Safe Electrical Equipment for Research." LAMS-7597, Los Alamos National Laboratory, Los Alamos, CA, April 1979.

** According to Rand, Leep, and Bradley (1979), a capacitor charged to 300 V with a stored energy of 30 J or more is considered lethal.

A recent incident at Aberdeen Proving Ground (APG) involving operation of a capacitor-bank power supply served as a reminder of the importance of the "safeing" operation. The findings of the committee appointed to investigate this incident prompted us to reconsider our procedures and to seek ways to decrease the possibility of future mishaps. In the second section of this report, we present some of the safety issues which we considered in these deliberations. We were led by these findings to develop a test circuit, described in Sections 3 and 4, to be used with a grounding-stick in order to provide a convenient indication of both continuity and acceptable resistance in the grounding circuit.

In the final section of this report, we discuss the incident at Range 18 and describe some hazardous situations which could have existed at the time of the "safeing" operation, as a result of the inferred malfunction. Use of the test circuit is illustrated by a discussion of its use in these hypothesized situations.

2. SAFETY CONSIDERATIONS

The resistors commonly used in grounding-stick circuits contain a liquid electrolyte. As an example, a solution of copper sulfate and water is used for the liquid electrolyte because it does not corrode the copper electrodes that are in contact, and it does not electrolyze when a current passes through it. These resistors are constructed by filling a nonconducting tube with a liquid solution and capping it at each end with a metal electrode. These resistors are also used as "dump" or "drain" resistors in the safety circuit of high-energy banks. These resistors are normally automatically connected to the capacitor bank at the completion of a run to remove any residual charge from the capacitors and to prevent voltage buildup due to dielectric relaxation. The dump resistors are also connected automatically in the event of electrical power failures, interruption of interlock circuits, or failures in the load circuit when the capacitor bank is charged. In these events, the dump resistors must absorb all the stored energy of the fully charged bank. If the dump-resistor system fails, then the grounding stick is the last resort to render the bank safe. Thus, the integrity of the grounding-stick circuit is very important.

One disadvantage of copper sulfate resistors is that their resistance may change with time. For example, air bubbles may accumulate around one of the metal electrodes breaking contact with the solution, or chemical reactions between the copper sulfate solution and the electrodes may occur. Additionally, contact resistance at the metal-liquid interface can make the measured resistance dependent on the voltage applied to the resistor. Therefore, the circuit resistance should be checked before the grounding stick is used. If the resistance is too high, the time needed to discharge a capacitor may be longer than expected by the operator which could lead to a hazardous condition. On the other hand, if the resistance is too low, due to a fault in the grounding-stick circuit, then an excessive current could flow through the circuit that might damage circuit components or injure the operator.

The test circuit described in this report facilitates checking the resistance of the grounding circuit before it is used. The check is made by touching the grounding stick to a metal plate which is connected to the test circuit. If the resistance is within the proper range, a light-emitting diode (LED) is turned on to indicate that the circuit is in good working condition. If the resistance is either too high or too low, an LED will not be turned on, which indicates that the grounding stick is not safe for use or that it has not been properly tested.

This test circuit has several advantages over the use of an ohmmeter. The operator need not remember the upper and lower resistances for the grounding stick; these resistances are preset in the test circuit itself. This is important when the capacitor bank is used infrequently or when different operators use the capacitor bank. Another advantage is that the test circuit is easy to use, which should encourage its use. The operator simply touches a metal plate with the grounding stick and observes the LED status. If an ohmmeter were used, the operator would first check the settings of the ohmmeter, attach the meter across the resistor, read it, and compare the reading with a written record. This does not mean, of course, that the test circuit completely eliminates the need for ohmmeters. Indeed, an ohmmeter should be used periodically to check the grounding stick circuit and the test circuit itself.

3. RESISTANCE TEST CIRCUIT

The test circuit contains two LM311 voltage comparators, IC1 and IC2 (Figure 1). IC1 checks for resistance values below the lower limit, whereas IC2 checks for resistance values

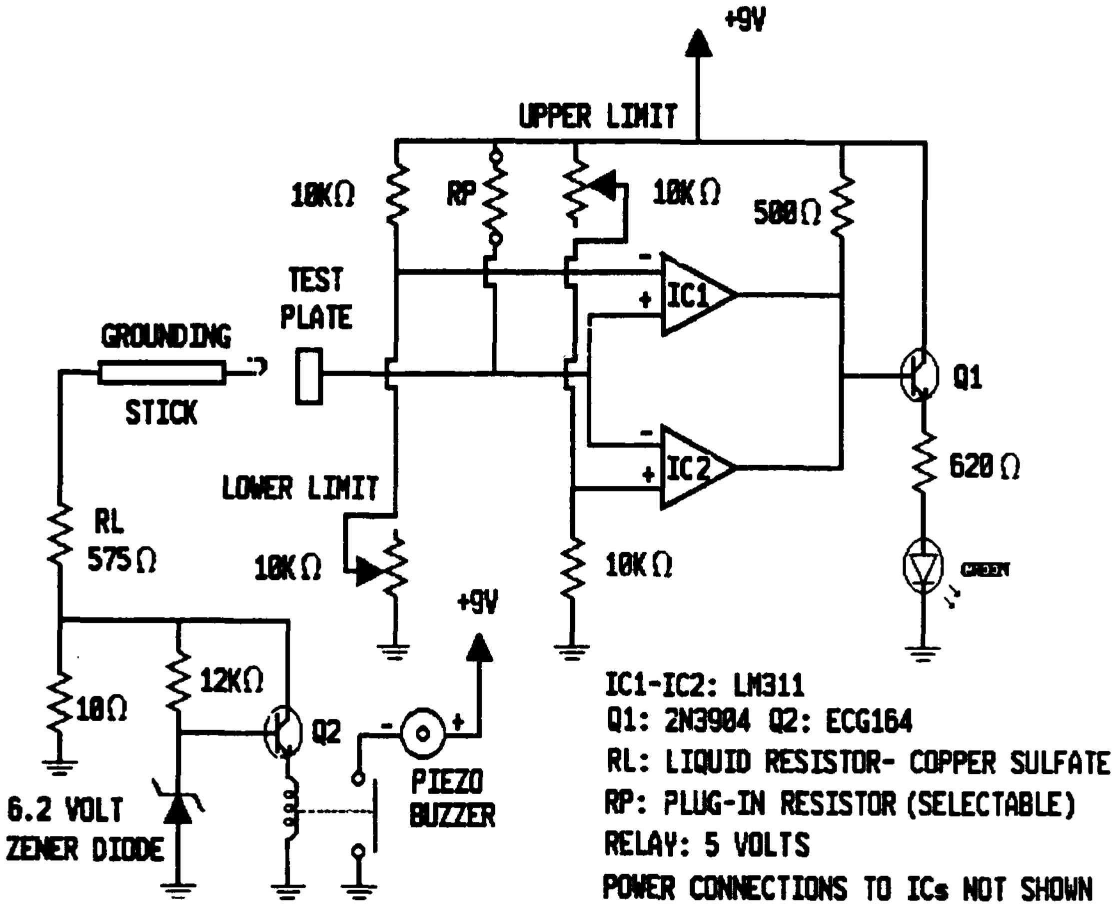

Figure 1. Schematic of the Grounding Stick Test Circuit and Current Sensing Alarm.

that are too high. These checks are carried out by comparing the voltage between the "+" (noninverting input) and the "–" (inverting input) on each voltage comparator. For this type of voltage comparator, if the voltage on the noninverting input is greater than the inverting input, then the comparator output is open. On the other hand, if the voltage on the noninverting input is less than that of the inverting input, the output is grounded.

Consider the operation of IC1, the low resistance detector. The inverting input of this stage is connected to a voltage divider that serves as a reference for the lower limit, adjustable from 0.0 V to half the power supply voltage. The noninverting input of IC1 is connected to another voltage divider formed by the grounding-stick resistor RL and the plug-in resistor RP, selected to have the same nominal resistance as that of the grounding stick resistor (Figure 1). If the grounding stick resistance RL is normal and the stick is touched to the test plate, the voltage on the noninverting input of IC1 will be half the power supply voltage, which is greater than the reference voltage on the inverting input; therefore, the output of IC1 is open.

Next, consider IC2, the upper limit detector. Its noninverting input is connected to a voltage divider that serves as a reference for the upper limit, adjustable from half the power supply voltage to the full power supply voltage. The inverting input of IC2 is connected to the voltage divider formed by RP and RL. If the resistance of RL is normal, the voltage on the inverting input will be half the power supply voltage, which is less than the reference voltage on the noninverting input. In other words, the voltage on the noninverting input is greater than the voltage on the inverting input, and the output of IC2 is open.

In summary, if the resistance of the grounding stick is too high, then the output of IC1 will be open and the output of IC2 will be a short. Conversely, if the resistance of the grounding stick is too low, then the output of IC1 will be a short and the output of IC2 will be open. If the resistance of the grounding stick is within the normal limits, then the outputs of both IC1 and IC2 will be open. These conditions are sensed by a logic gate that turns on the LED only when the outputs of IC1 and IC2 are both open. This logic gate is formed by connecting the outputs of IC1 and IC2 together along with a 500-Ω pull-up resistor and the base of the transistor Q1 which drives the LED. The outputs of IC1 and IC2 now act as two parallel switches to ground, and both switches must be opened to disconnect the base of the transistor from ground. Once the base of the transistor is disconnected from ground, the voltage on the base is pulled up close to the supply voltage by the 500-Ω resistor turning on the transistor and the LED.

4. CURRENT SENSING CIRCUIT

This test circuit indicates the existence of residual charge on a capacitor by a current flow when the grounding stick is connected to the center terminal. The circuit in parallel with the 10-Ω resistor in Figure 1 indicates that a current of more than about 0.5 A is passing through the grounding stick by activating a piezobuzzer. Thus, the piezobuzzer will sound when the voltage at the end of the grounding stick is > 300 V. This gives the operator an audible alarm that a charge is being bled from the capacitor. Since the alarm is audible, the operator can keep his eyes on the grounding stick and the capacitor terminal during the grounding procedure.

The 5-V reed relay in Figure 1 is driven by a circuit that limits the voltage across the coil to about 5 V to prevent damage to the relay. As an example, if the capacitor were charged to 11 kV, the voltage across the 10-Ω resistor would be 190 V. This circuit consists of a high-voltage transistor, Q2, that has an emitter-to-collector rating of 800 V; a 12-kΩ resistor; and a 6.2-V zener diode. The zener diode keeps the base of Q2 fixed at 6.2 V, and since the voltage from the base to the emitter is about 0.7 V for a conducting transistor, the voltage across the coil of the relay is thus limited to about 5.5 V for any period when the voltage across the 10-Ω resistor is greater than about 5.5 V.

5. A RECENT INCIDENT AT ABERDEEN PROVING GROUND (APG)

On 31 October 1990, an employee of a visiting contractor was injured at Range 18, APG, MD, while working on a capacitor bank that had malfunctioned during its most recent charge cycle. The bank was thought to have been properly discharged and safed following the malfunction.* We describe this incident in some detail to illustrate how use of the test circuit described herein would have eliminated some of the possibilities for serious injury that existed or could have existed as a result of this particular malfunction.

The capacitor bank operator, a fellow employee, had checked the grounding stick with an ohmmeter before the capacitor bank malfunctioned, though not just after the incident nor immediately before actual use. The grounding stick was checked and found to be in good working condition after the injury occurred. However, because there was extensive damage to the capacitor bank, the possibility that the grounding stick could have been damaged by the malfunction was real. Therefore, the operator could have been in jeopardy due to the use of a damaged grounding stick that was assumed to be in good working condition. The use of our test circuit would have eliminated this possibility.

* Eccleshall, D. "Technical Investigation of Incidents on Range 18 on 31 October 1990 at FMC Electrothermal - Chemical Gun Pulsed Power Facility." Internal Report, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, MD, 27 December 1990.

During the "safeing" operation, the operator noticed a small spark when he touched the terminal of a particular capacitor with the grounding stick indicating the presence of charge on the capacitor. He then kept the grounding stick on the terminal for about 10 seconds to completely discharge the capacitor. Next, he placed a short between the case of the capacitor and a bus bar that is connected to the terminal of the capacitor by a fuse, a very poor grounding procedure concluded the committee appointed to investigate the accident. Unfortunately, this fuse had been blown by the malfunction. Thus, this particular capacitor had no drainage or leakage path across it after the safeing procedure and subsequently became recharged by dielectric relaxation, resulting in injury to a second contractor employee when he touched the terminal 30 minutes later during repairs.

It is easy to imagine a plausible scenario which could have made the accident far more serious. Suppose the operator had not noticed the small spark and assumed that there was no charge on the capacitor. Such a sequence of events could have occurred either because the operator's attention was temporarily diverted or his view of a small arc was obscured. Thus, he could have removed the grounding stick before the capacitor was completely discharged. The current-sensing portion of the present circuit would have alerted the operator by a buzzer that a charge was being drained from the capacitor, even when no sparks were observed. Thus the use of a test circuit similar to that shown in Figure 1 would have prevented the injury which occurred in the incident described by Eccleshall.

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